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How do Wind and Solar Power Affect Grid Operations: The Western Wind and Solar Integration Study

Preprint

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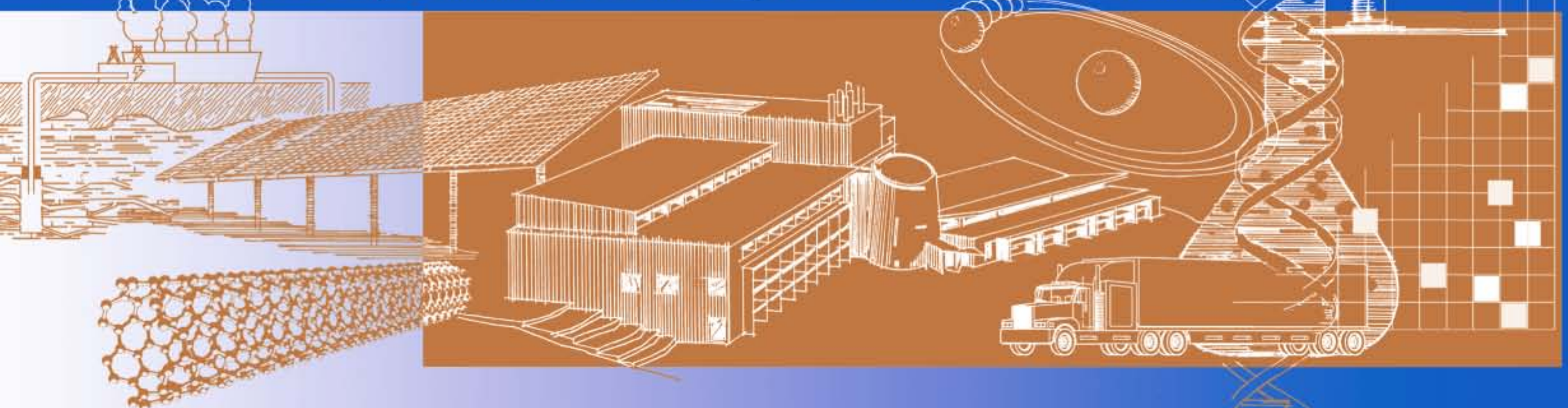

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How do Wind and Solar Power Affect Grid Operations: The Western Wind and Solar Integration Study

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***Abstract* — The Western Wind and Solar Integration Study is one of the largest regional wind and solar integration studies to date, examining the operational impact of up to 35% wind, photovoltaics, and concentrating solar power on the WestConnect grid in Arizona, Colorado, Nevada, New Mexico, and Wyoming. This paper reviews the scope of the study, the development of wind and solar datasets, and the results to date on three scenarios.**

***Index Terms* — grid integration, wind power, solar power, transmission, power system operation, reserve requirements.**

I. INTRODUCTION

The Western Wind and Solar Integration Study (WWSIS) is one of the largest regional wind and solar integration studies to date [1]. It was initiated in 2007 to examine the operational impact of up to 35% energy penetration of wind, photovoltaics (PV), and concentrating solar power (CSP) on the power system operated by the WestConnect [2] group of utilities in Arizona, Colorado, Nevada, New Mexico and Wyoming. WestConnect also includes utilities in California, but these were not included because California [3] had already completed a renewable energy integration study for the state. [See Fig. 1] This study was set up to answer questions that utilities, PUCs, developers, and regional planning organizations had about renewable energy use in the west:

- Does geographic diversity of renewable energy resource help mitigate variability?
- How do local resources compare to out-of-state resources?
- Can balancing area cooperation help mitigate variability?
- What is the role and value of energy storage?
- Should reserve requirements be modified?
- What is the benefit of forecasting?
- How can hydro help with integration of renewables?

The WWSIS is sponsored by the U.S. Department of Energy (DOE) and run by the National Renewable Energy Laboratory (NREL) with WestConnect as a partner organization. The study was originally established to follow onto DOE's *20% Wind Energy by 2030* report [4], which did not find any technical barriers to reaching 20% wind energy in the continental United States by 2030. This study and its partner study, the Eastern Wind Integration and Transmission Study, performed a more in-depth operating impact analysis to see if 20% wind energy was feasible from an operational level. In DOE/NREL's analysis, the 20% wind energy target required 25% wind energy in the western interconnection; therefore, this study considered 20% and 30% wind energy to bracket the DOE analysis. Additionally, since solar is rapidly growing in the west, 5% solar was also considered in this study.

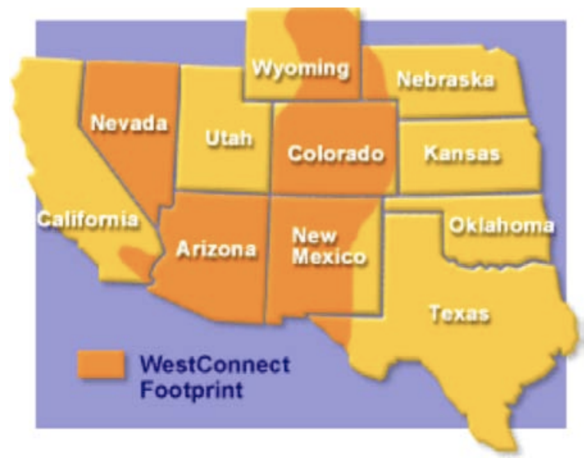

Fig. 1. WestConnect group of utilities.

The goal of the WWSIS is to understand the costs and operating impacts due to the variability and uncertainty of wind, PV, and CSP on the grid. This is mainly an operations, not transmission study, although different scenarios model different transmission build-outs to deliver power. The study does not focus on the cost of generating wind or solar power, but rather the operational costs and savings due to fuel and emissions.

II. MAJOR TASKS

In the WWSIS, the major tasks consisted of utility data collection, wind and solar dataset development, scenario development, statistical analysis, production simulation analysis, quasi-steady-state analysis, and analysis of mitigation options. The WWSIS was a large team effort, with Exeter Associates running data collection, 3TIER Group developing the wind dataset and the solar forecasts, SUNY/Albany modeling the solar resource, NREL modeling the PV and CSP power plants, Northern Arizona University (NAU) validating the wind dataset, and GE developing scenarios and conducting the analysis.

In this study, we modeled the year 2017 three times, with the historical load and weather patterns from 2004, 2005, and 2006. In this way, we examined interannual variability, which was not insignificant. It was important in this study to model not only the 35% renewable energy penetration within the study footprint, but also a significant (up to 23%) renewable energy penetration in the rest of the western interconnection, to address concerns of 'exporting the variability', which have occurred in some other studies that have ignored significant renewable energy penetrations outside the area of interest.

III. WIND DATA DEVELOPMENT

3TIER Group developed the wind dataset for the study [5]. Over 75 GW of wind power sites needed to be modeled in the study. Lacking sufficient measurements to represent this wind build-out, it was decided to model the wind resource across the western United States to generate a consistent wind dataset in space and time. 3TIER Group used the Weather Research and Forecasting (WRF) mesoscale Numerical Weather Prediction Model (NWP) over the western United States at a 2-km, 10- minute resolution for 2004-2006. In order to run the large region at this high a resolution, the region had to be split up into four domains which were run independently and then merged. The domains were run in three-day blocks which were merged together and the seams smoothed. While the seams were smoothed so that variability did not exceed realistic limits, the days with seams exhibited significantly more variability than the days with without seams.

3TIER Group also developed day-ahead wind forecasts for each hour. To eliminate any systematic errors that would result in the forecasts being 'too good', a different input dataset was used for these model runs. The forecasts were run using a coarser resolution than the 2-km resolution of the 'actuals' dataset.

Over 960 GW of wind sites (32,000 sites of 30 MW each) were modeled, allowing for various scenarios as well as future studies to be run. Each 2-km x 2-km grid cell was assumed to contain 10 Vestas V90 3-MW wind turbines, yielding 30 MW per grid cell. Actual wind plants do not exhibit a deterministic 'wind plant power curve,' so instead of using the sum of 10 Vestas V90 wind turbine power curves, 3TIER Group's stochastic SCORE methodology was used for power conversion [5]. The SCORE methodology uses measured probability density functions to produce the type of stochastic output that is observed in actual wind plants. While array and electrical losses were not explicitly taken into account in the power conversion, the wind plant output tended to correspond most closely to a net wind plant output and was used as such. The wind dataset is publicly available [6].

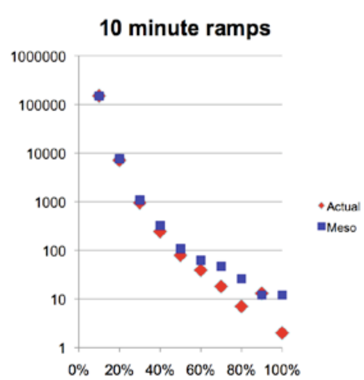

Fig. 2. Validation of the variability of the wind dataset, comparing the 10-minute wind plant output deltas of the actual wind plant output and the mesoscale modeled dataset over a three year period. The dataset is considered to be conservative because it overestimates the variability of the wind.

To assess the usefulness of this dataset for the WWSIS, extensive validation was undertaken on the dataset. Because this was the first time such a large, high resolution wind dataset had been created, it was critical to check the data in as many ways as possible. This included checks of the power curve, maximum and minimum output, largest ramps, average capacity factor, etc.

3TIER Group, NREL, and NAU validated the dataset against meteorological tower measurements of wind speed. In some cases, this was used to determine whether large wind ramps were real or artifacts of the model process. NREL also validated the dataset against wind plant output for nearly over 1 GW of wind plants for which NREL could access data. The most critical check of a dataset for integration analysis is the accuracy of ramps, in this case, on a 10-minute and hourly timescale. A consistent over- or under-production bias is less important in assessing operational impacts. The wind dataset validation [See Fig. 2] showed that the dataset typically had higher variability than the actual wind plant output, indicating that the results are conservative, from a utility's reliability perspective.

IV. SOLAR DATA DEVELOPMENT

The State University of New York (SUNY)/Albany developed the solar resource dataset for the study. SUNY/Albany used a satellite cloud cover model run over the United States at a 10-km, hourly resolution [7]. This dataset includes global horizontal, direct normal and diffuse radiation.

PV was modeled in the WWSIS as distributed generation on rooftops because of the limited knowledge at that time of the variability of large, central station PV. Preliminary data, analysis, and operating experience from the 4.6-MW Springerville Generating Station Solar System in Arizona indicated that central station PV could have significant impacts on the grid, but there was little other data to determine whether the Springerville climate was an anomaly or typical. Weather stations in the western United States were modeled using PV Watts to create PV output in block sizes of 100 MW. In order to model distributed generation, PV Watts was run using 11 different configurations of tilt, orientation, and tracking/flat-plate and outputs were aggregated. The hourly PV profiles are available on the web [8].

To downscale the PV output to a 10-minute resolution, NREL developed a model that compared the hourly average PV output to the clear sky (no clouds) PV output and added variability. The amount of variability added was based on measured PV output from many small PV plants in Arizona Public Service's Solar Test and Research (STAR) program, the Springerville system, and several small PV plants in Colorado.

CSP was modeled in the WWSIS as 100-MW blocks of parabolic trough plants with 6 hours of thermal storage. Over 200 GW of CSP plants were modeled in the study and these profiles are available on the web [9]. The storage was initially dispatched to a typical utility load pattern (in this case, Southern California Edison). Six hours of storage requires that the solar field (solar collectors) be approximately twice as large as a system without storage. The Solar Advisor Model [10] was used for the power conversion using NREL's

Excelergy model to represent the parabolic trough plants with thermal storage. Losses associated with the thermal storage are estimated to be minimal for storage of several hours. Because the CSP with thermal storage produces a very stable output, the 10-minute dataset was created simply by interpolating the hourly dataset.

V. SCENARIOS

A large number of transmission projects are being planned in the Western Electricity Coordinating Council (WECC). To better understand the trade-offs between using local and remote resources, two ‘bookend’ scenarios were established – an In-Area (IA) scenario using local resources and a Mega-Projects (MP) scenario using higher quality, remote resources. Additionally, a ‘middle ground’ scenario – the Local Priority (LP) scenario – was created to look at a more realistic buildout of sites and transmission. The WestConnect footprint was modeled by physical transmission area, where transmission area was defined by a combination of respecting physical transmission areas and trying to match transmission areas as much as possible to state boundaries. [See Fig. 3]

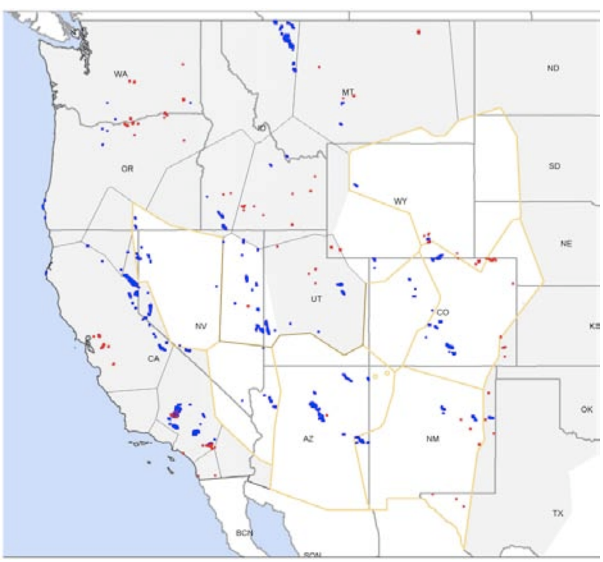

Fig. 3. The transmission areas modeled in the WestConnect study footprint are shown in white, and roughly match the boundaries of the corresponding state.

The IA scenario was built by selecting the best sites according to a mix of energy value, geographic diversity, and capacity value in each transmission area to make up each penetration level. The MP scenario was built by trading out the lowest ranked sites of the IA scenario for sites that had a lower capital cost (taking into account capital equipment, transmission to the area being served, and losses). This included the following cost assumptions: $1600/MW-mile transmission capital cost; $2000/kW wind capital cost; $4000/kW solar capital cost; and 1% losses per 100 miles cost penalty. The transmission build-out was then ‘rationalized’ so that transmission lines used typical transmission ratings and smaller ties were consolidated or disregarded as appropriate. The LP scenario was built similarly to the MP scenario, but with a 10% cost benefit for in-area wind and solar sites. [See Fig. 4] It is understood that some intra-area transmission build-out is needed for each of the scenarios, but this was not included in the costing of the scenarios.

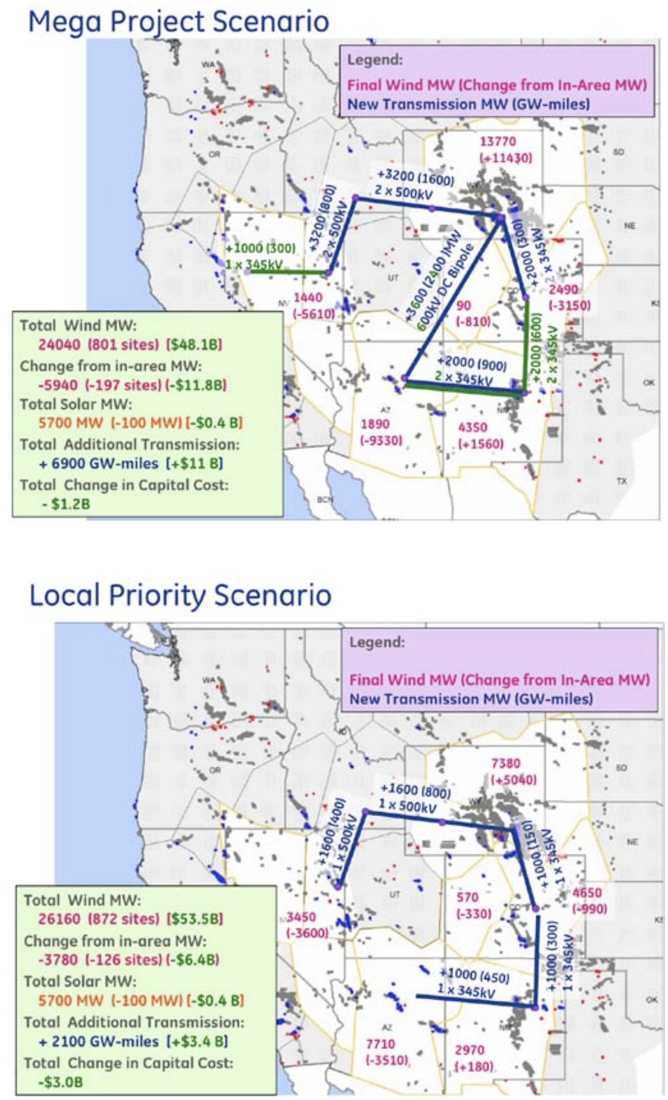

Fig. 4. MP and LP scenarios at 30% wind (shown in blue and red dots) and 5% solar energy penetration.

TABLE I. Wind and solar penetration levels (by energy) used in the study.

Scenario name	Study Footprint		Rest of WECC	
	Wind	Solar	Wind	Solar
Baseline	Existing Wind & Solar sites			
10	10%	1%	10%	1%
20	20 %	3%	10%	1%
30	30 %	5%	20%	3%

The scenarios were run on three levels of penetration as shown in Table I. The solar consisted of 70% CSP and 30% PV.

VI. GENERAL RESULTS

The study is not yet complete, but there has been a tremendous amount of data development and analysis conducted to date [11]. Some major insights gleaned thus far in the study are:

- Balancing area coordination is imperative to integrate 35% renewables in the study footprint.
- Aggregation of wind and solar sites mitigates the relative impacts of the large ramps.

- •The operational impacts do not differ much between using local resources versus remote, higher quality resources. The overall cost savings, displaced generation, spot prices, etc. are very similar.
- •What happens in the study footprint depends very much on what is happening in the rest of WECC. The study footprint typically exports power to WECC, but this decreases significantly when the renewables penetration in the rest of WECC increases from 11% to 23%.
- •Pumped hydro storage usage increases but no need for increased pumped hydro storage was identified.
- •Perfect forecasts have a modest benefit over state-of-the-art forecasts.

VII. STATISTICAL ANALYSIS

GE conducted statistical analysis on the 10-minute and hourly datasets. As discussed in section III, the wind data was modeled in three-day blocks and the seams were smoothed, but increased variability was identified in the dataset every third day. Therefore, every third day was removed from the dataset and the statistics scaled up by 50% to simulate a full year. Key findings include:

- •There is significant year-to-year and month-to-month variation in energy from the wind and solar. There is less scenario-to-scenario variation in the study footprint's energy from the wind and solar.
- •The size of the area (in terms of MW load) matters. For small areas, such as Wyoming, wind can easily provide over 100% of the load needs. This study finds that high penetrations of wind and solar cannot be met without some kind of cooperation between balancing areas.
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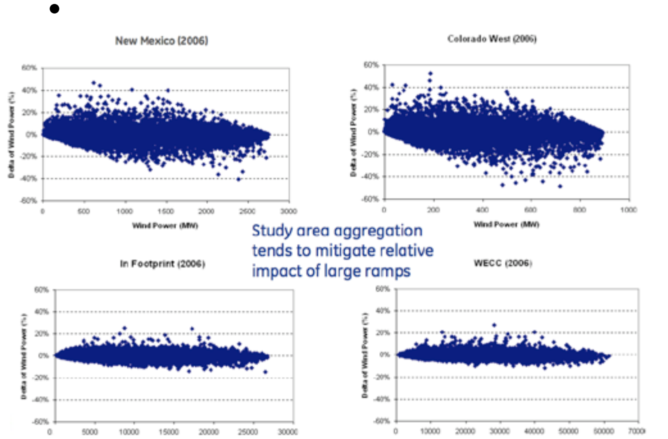


Fig. 5. Actual wind output versus hourly wind output delta as percentage of installed wind capacity at a 30% wind penetration level. Top left: New Mexico; top right: Colorado West; bottom left: study footprint; bottom right: all of WECC.

- •Geographic diversity helps mitigate variability. The relative variability in any particular state is much higher than the relative variability of the aggregated study footprint. Interestingly, the variability does not decrease much in going from the study footprint to the entire WECC region. [see Fig. 5]
- •Drops in wind and solar combined with evening load rise drive extreme net load up-ramps in late afternoons during the late fall and winter. Extreme down-ramps are driven by summer/early fall evening load roll-off.

Fig. 6 shows the study footprint's net load in the month of April and July. In April, when the wind is strong, the operator faces significant challenges in meeting the net load and there is a time on April 15 when the net load is negative. In contrast, in July, when the wind is weak and the solar is strong and coincident with load, the net load is very similar to the load alone.

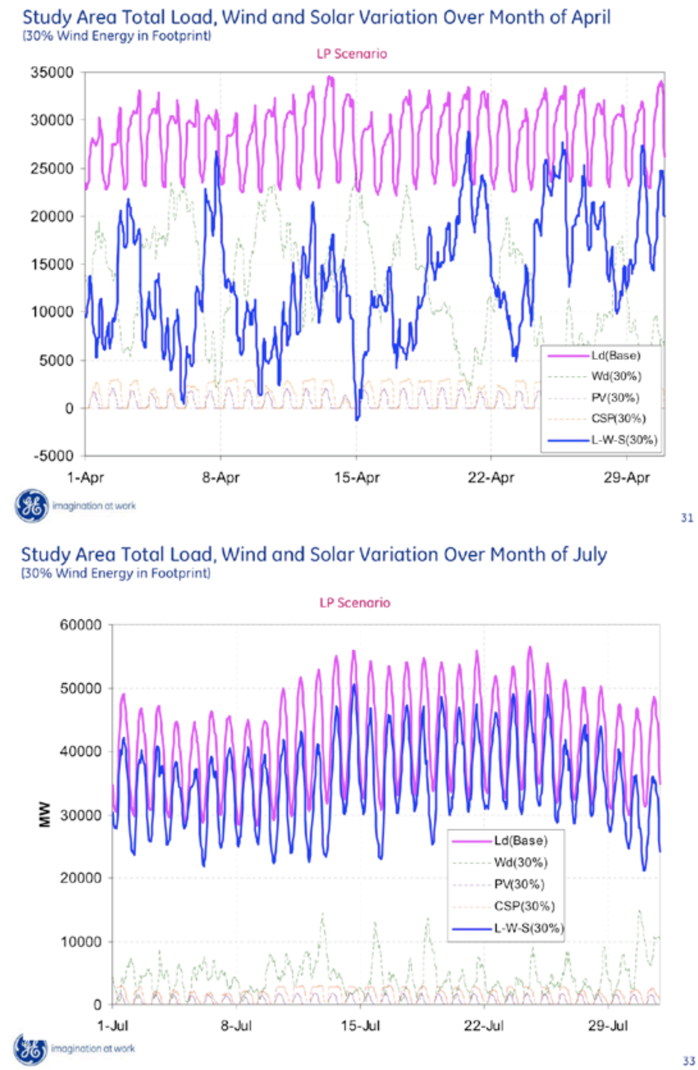


Fig. 6. Net load during the month of April 2006 (top) and July 2006 (bottom) for the LP scenario with 30% wind, 5% solar penetration. The load (pink) is what the operator formerly had to meet. The wind (dashed green), PV (dashed purple), and CSP (dashed orange) generation is shown. The net load (blue) is what the operator now must meet in a high renewables penetration world.

Fig. 7 shows the hourly load ramps versus the hourly wind ramps for the LP scenario. In Q1 and Q3, the load and wind deltas offset each other – the wind helps the operator balance the system. In Q2 the wind is increasing while the load is decreasing – these are times when the wind could potentially be curtailed to help the operator balance the system. It is Q4 that is of greatest concern to operations – these are events when the load is increasing but the wind is dropping off. Without wind, the maximum hourly load delta is 3674 MW. With wind, the net load delta exceeds that maximum 66 hours during the year of 2006. From this, a good case can be made for programs that incent interruptible load.

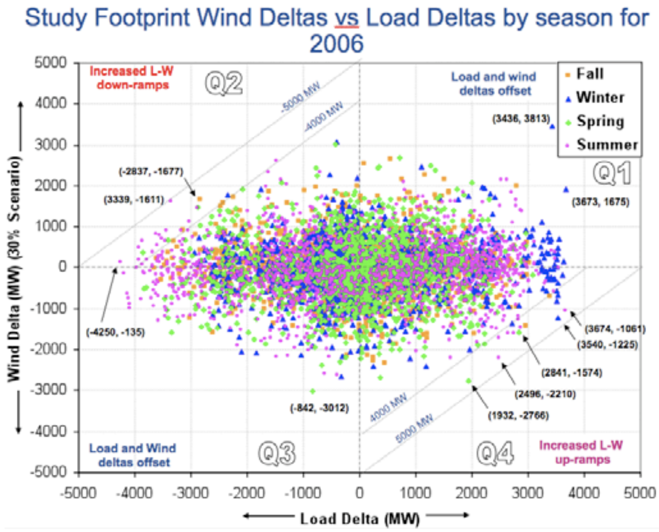


Fig. 7. Study footprint wind deltas versus load deltas by season for 2006, based on the 35% renewable energy LP scenario. In Q2, there are 3 hours where the net load down-ramps are more than the largest load-alone down-ramp. In Q4, there are 66 hours where the net load up-ramps are more than the largest load-alone up-ramps.

VIII. OPERATIONAL ANALYSIS

GE conducted hourly production simulation analysis of the 3 scenarios at 3 renewable energy penetration levels over the three years using MAPS. Here the full wind dataset was used, but results were checked to ensure the increased 3rd day variability did not lead to unrealistic results. The following assumptions were used: $2/MBTU coal price, $9.5/MBTU natural gas price, and $30/ton of carbon dioxide tax. An economically rational, WECC-wide commitment and dispatch was undertaken recognizing transmission limitations. Additional capacity of 24 GW was added to the existing system to maintain reserve margins. Operating savings were calculated, reflecting the avoided cost of fuel and emissions, and losses in efficiency due to plants not operating at optimal output. 'Wear and tear' costs due to increased or harder cycling of units were not taken into account because these have not been adequately quantified.

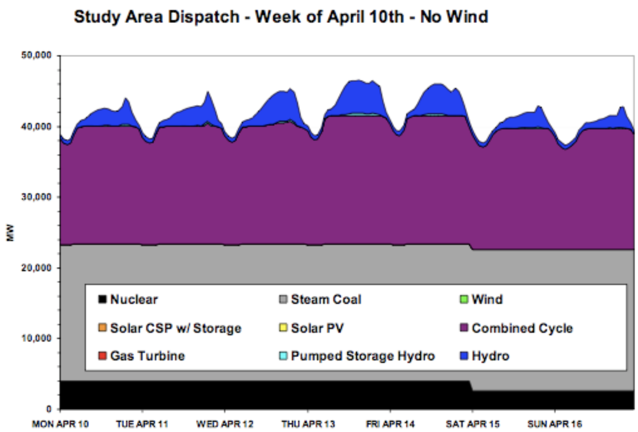
The wind 'forecasts', which were developed using a separate input dataset from the wind 'actuals', had a positive bias of approximately 10% in the study footprint and 20% outside the study footprint. As a result, a sensitivity analysis was done on the forecasts using the raw forecasts, and the forecasts were discounted by increasing amounts.

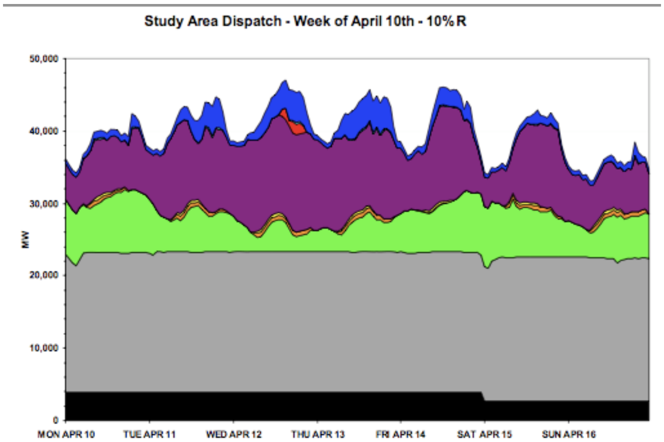
The production simulation analysis across the three (IA, LP, MP) scenarios showed the following results:

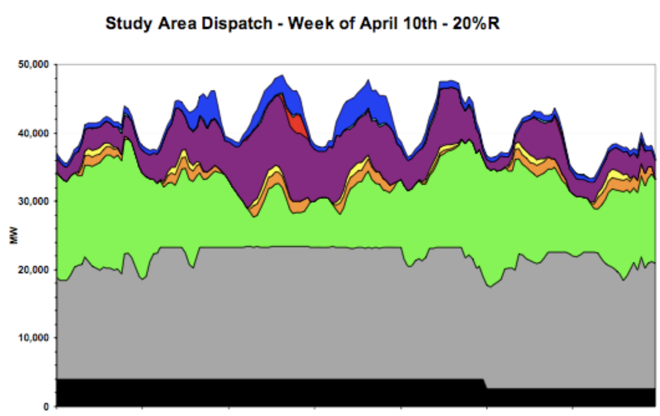
- Interestingly, no significant variation in operational results were found between the various scenarios. There was significant difference, however, in the different renewable energy penetration levels.
- Forecasts are critical. There are significant variations in impact for the same wind variability with different forecasts.
- No significant operational issues were identified at penetrations up to 23% in the study footprint and 11% outside the study footprint. The impact is more severe at 35% inside the study footprint and 23% in the rest of WECC.
- The operational impact is dependent on what your neighbor is doing. As the penetration increases from 23% inside the footprint and 11% in the rest of WECC to 35% inside the footprint and 23% in the rest of WECC, exports from the study footprint decrease by about 10%.
- For a perfect forecast, increased renewable energy penetration drives the spot prices lower. Because there are some forecast errors, these errors drive the spot prices in the 35% renewables case back up.
- Displaced generation is mostly combined cycle and gas turbine units. At 35% renewables, coal units are also starting to be displaced.
- The operational cost savings due to fuel savings and emissions displacements are slightly over $20B, or $82/MWh, for all of WECC in the IA scenario. The value of the renewable energy forecast for the 35% renewables case for all of WECC is about $2.20/MWh.
- The incremental value of renewables based on spot price revenue in the IA scenario in the study footprint is around $60/MWh for the CSP and PV energy and about $38/MWh for wind energy. For all of WECC, this decreases to around $50/MWh for the CSP and PV and slightly more than $30/MWh for wind.
- With higher penetrations of renewables, unserved energy increased significantly (from negligible to 46 GWh as the renewables penetration increased from 23% to 35% in the IA scenario) due to occasional over-forecasting of wind generation. By discounting the wind forecast from 0 to 25% in the IA 35% renewables scenario, unserved energy drops dramatically from 46 to 4 GWh, which is tiny compared to the total study footprint load being met of 286,000 GWh. Spilled energy increases only slightly from about 780 to 960 GWh, which is small compared to the total study footprint renewable energy generation of 100,000 GWh.
- At higher penetrations, it is essential that the load be an active participant such as through interruptible load or demand response programs. Interruptible loads are easily cost justified, with average costs of reducing unserved energy of around $6000/MWh when the forecast is discounted by 10%.
- Year to year comparisons did not show significant changes in results.

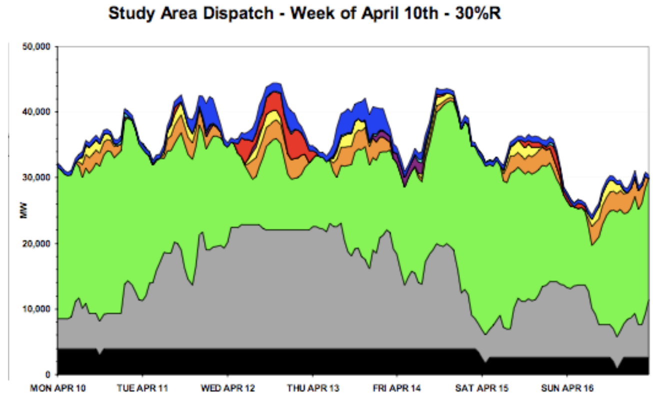
Fig. 8 shows the operation of the system going from no new renewables to 11% to 23% to 35% renewables using the IA scenario during a week in April 2006. At 35% renewables, the combined cycle units are almost completely off, gas turbine output has increased, and the coal plants are cycling significantly. Even the nuclear units are trying to cycle some, which more likely would indicate a need to spill some of the wind generation. Total generation inside the study area drops because the rest of the WECC, with 23% renewables penetration, is now reducing their need for imports from the study area. This particular week in April was a severe wind week. Other months did not have as much impact. The 5th plot shows operation for a week in mid-July for the 35% penetration scenario, which did not seem to present any operational strain on the system.

Hydro operation was examined in detail. The scenarios were run with the hydro scheduled after the forecasted wind and solar was taken into account. The hydro schedule varied with increasing renewable energy penetration. There was an economic impact of not rescheduling the hydro based on the renewable power forecasts.









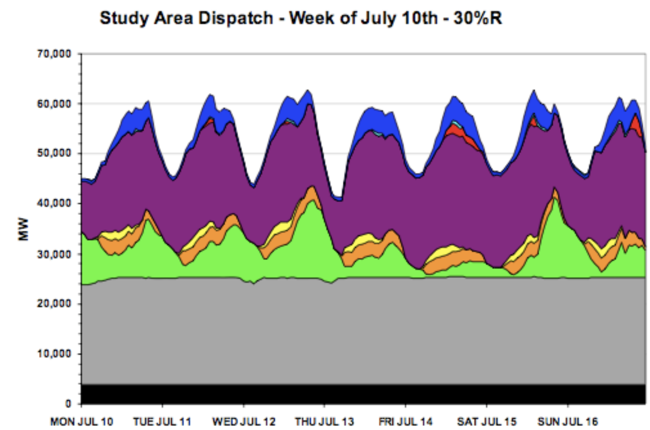


Fig. 8. Dispatch of units in study footprint for April 2006: Top: baseline case with no new renewables; 2nd: 11% renewables; 3rd: 23% renewables; 4th: 35% renewables; and the 5th shows the 35% renewables case but in July 2006.

Additionally, the pumped storage hydro (PSH) operation was investigated. While PSH usage increased with the higher penetrations of renewables, it did not top-out. This indicated that no need for additional PSH was called for in the study. This seemed counterintuitive, so the PSH was encouraged to run more, by discounting the pumping costs. However, that led to an increase in total variable costs, justifying the initial conclusion that additional PSH or additional usage of the existing PSH was not needed.

A sensitivity analysis was run on the gas price, due to the extreme volatility of gas prices in recent years. The base cases assumed \$30/ton of carbon dioxide, which translates to an adder of \$0.60/MWh for combined cycle and \$1/MWh for coal units. Decreasing the gas price from \$9.5/MBTU to \$3.5/MBTU shifts the displaced units from the combined cycle and gas turbine units to the steam coal units, and decreases operational cost savings by about 40%.

A sensitivity analysis was run on the transmission build-outs, by running the LP and MP scenarios without the requisite transmission. That is, the better quality resource sites were built out but additional transmission to bring those resources to load was not built out. This essentially replicates the transmission buildout of the IA scenario but shifts the renewable energy sites to different locations. The unserved energy at 35% renewables remains pretty constant between the IA scenario and the LP and MP scenarios with zero inter-area transmission. The spilled energy roughly doubles from the IA scenario to the LP with zero inter-area transmission, and increases tremendously to approximately 20% of the wind output in the MP scenario with zero inter-area transmission.

IX. Reliability Analysis

Reliability analysis was conducted on the study footprint without transmission constraints to determine the capacity value of the renewable resources compared to the generation resources and load profiles. Capacity values for the three penetration levels for the IA scenario in 2006 are shown in Table II. It should be noted that the PV capacity rating was done on the DC output of the panels, resulting in an AC rating that is 23% lower. Thus the PV capacity value is lower than one would expect if the rating was done on the AC output.

TABLE II. Capacity Value analysis

Penetration level	Wind+ CSP+ PV	Wind only	CSP only	PV only
10% wind, 1% solar	15.8%	11.4%	92.6%	28.6%
20% wind, 3% solar	17.7%	10.8%	93.3%	26.9%
30% wind, 5% solar	18.5%	10.7%	92.2%	26.9%

The significantly higher capacity value of CSP serves to highlight the benefits of the CSP with thermal storage in meeting peak demand. Fig. 9 shows how much better the CSP with storage matches up to the late afternoon peak demand than the PV.

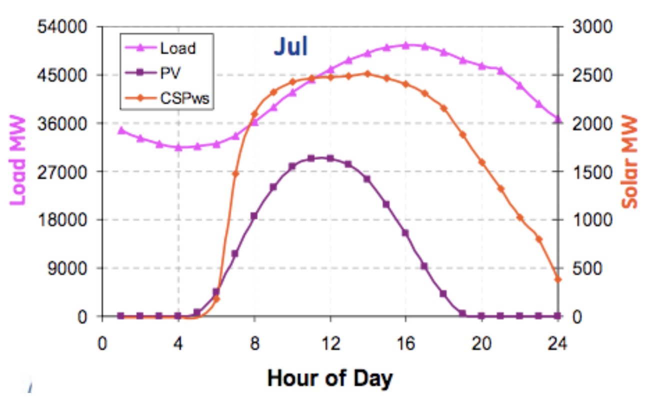


Fig. 9. Diurnal profiles of the study footprint load, PV, and CSP (with 6 hours of thermal storage) for the LP scenario of 5% solar energy penetration.

The capacity values were also run for the LP and MP scenarios and found to be fairly consistent across scenarios.

X. Next Steps

The study is anticipated to be complete in early 2010, with a draft report and stakeholder meeting to be held at the end of 2009. The next steps in this study are to complete the IA, LP, and MP analyses, including the quasi-steady-state simulation of specific, difficult events at 1-minute time resolution. Intra-hour variability is also underway and the implications of high penetrations of renewables on reserve requirements are being assessed.

The study originally anticipated undertaking additional scenarios, but because the operational impacts of the three scenarios did not show great differences, the study will instead focus on other analysis before it is completed in early 2010. The LP scenario will be re-run with a 23% renewable energy penetration in both the study footprint and the rest of WECC so that the results from stepping up from the 23% renewables (11% in rest of WECC) to the 35% renewables (23% in rest of WECC) can be understood. A second analysis will examine the role of storage on different timescales and look at the value of storage for various penetration levels. Plug-in hybrid electric vehicles and demand response will be considered in this analysis.

Additional analysis may include an examination of the non-renewables balance of the generation portfolio. The analysis conducted to date includes 24 GW of capacity additions to the existing system. It would be useful to examine variations on these additions in terms of flexible generation, or perhaps retirements scenarios of existing non-flexible units, or replacing some capacity additions with PSH.

After this study is complete, the next logical step would be to expand this study to include all of WECC, including Canada. Inclusion of large utility-scale (100 MW and up) PV plants would be important, since plants of this size are currently in interconnection queues in WECC. However, there is not much known about the variability of large, utility-scale PV plants on a fast time scale. Data collection, analysis, and better modeling are needed to be able to include large PV plants in such an integration study.

XI. References

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